

Physical description of the blood flow from the internal jugular vein to the right atrium of the heart: new ultrasound application perspectives

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Published on 5 March 2016.

Ikken hissatsu (拳必殺) means something like *to annihilate at one blow*. This document is part of a series of notes each one targeting a single goal. Each note has to *annihilate at one blow*!

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BACKGROUND

The brain drainage is due to the venous blood flow directed from the brain to the heart through the internal jugular veins (IJVs), epidural veins and vertebral veins (see Fig. 1). The brain-heart direction indicates that there must be a negative pressure gradient driving the blood flow (i.e. the pressure in the brain is higher than the pressure in the pressure in the right atrium (RA)). The pressure, where the IJVs begin, is the residual arterial pressure and, despite its pulsatile nature, in this study it is considered to be constant.

The pressure in the RA varies according to the cardiac cycle. Its trace presents two wave peaks called a and v

and two waves minima called x and y . Such waves have a precise phase relationship with the ECG waves PQRST [Applefeld(1990)], see Fig. 2. The waves a , x , v and y are also detectable at level of the neck due to the internal jugular vein (IJV) pulsation[Mackenzie(1902)].

The pressure changes generated in the RA are indeed transmitted to the IJV and affect the velocity of the blood in two ways i) modifying the pressure gradient so that it is no longer constant over time and generates a non-steady flow [Sisini et al.(2016), Kalmanson et al. (1972)], ii) cyclically varying the CSA of the IJV [Sisini et al.(2015)]. Since the walls of the IJVs are neither rigid nor collapsed, the pressure variations generated in the RA are transmitted to the IJV as a pressure wave with finite

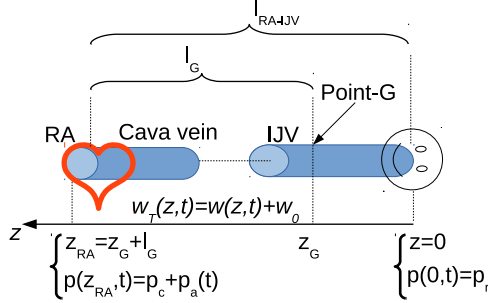


Figure 1: Geometrical model of the jugular-heart segment. The z axis is positive in the jugular-heart direction. l is the distance between the RA and point G in which the scan takes place. Blood velocity is indicated by w .

propagation velocity c . Such pressure waves are responsible for the modulated component of the velocity of blood in the IJV. For this reason, their wave equation can be used to derive the instantaneous velocity of the blood even in the absence of a direct measurement of such parameter obtained, for example, by using an ultrasound Doppler scanner. A first attempt to this goal was presented in [Sisini et al.(2015b)], where the instantaneous velocity of the blood in the IJV was determined qualitatively, for one cardiac cycle, using the Womersley equation [Womersley(1955a), Womersley(1955b), Womersley(1955c)].

Physical description of the RA-IJV segment

The RA-IJV system is represented in Fig. 1 as a tube with a circular section. G indicates a reference point on the right IJV. The $w(z, r, t)$ function represents the velocity of the blood in the z direction. It depends on z coordinate, on r (the distance from the axis z) and on t (the time). The symbol $\bar{w}(z, t)$ is used to indicate the blood velocity averaged over the CSA. The pressure at the right end of the tube ($z = 0$) is the residual arterial pressure and it is assumed to have a constant value p_r while at the left end of the tube ($z = z_{RA}$) the pressure

feels the effects of the RA activity varying periodically with the cardiac cycle. The pressure at $z = z_{RA}$ (see Fig. 1) is supposed to be the sum of a component p_c constant in time and of a periodic component $p_a(t)$ which varies according to the atrial cardiac activity. The blood flow is due to the pressure gradient between the ends of the cylinder. It produces a velocity $\bar{w}_T(t)$ that results from a constant component w_0 due to the constant gradient $\frac{p_c - p_r}{l_G}$ and a time varying component $\bar{w}(t)$ due to the time varying $\frac{p_a(t) - p_r}{l_G}$. This system can be described using the Womersley equation that is a linear differential equation where the unknown is the function w and the pressure gradient $(\partial p(t)/\partial z)$ is the source term:

$$\frac{\partial^2 w(r, z, t)}{\partial r^2} + \frac{1}{r} \frac{\partial w(r, z, t)}{\partial r} - \frac{\partial w(r, z, t)}{\partial t} = \frac{1}{\mu} \frac{\partial p(t, z)}{\partial z} \quad (1)$$

The radial component of the blood velocity and the non-linear terms of the equation are negligible for $c \gg w$. [Womersley(1955c)] The solution of Eq.1 and the complete procedure to calculate it are explained in detail in [Sisini et al.(2015b)]. However the solution is there defined up to the multiplicative constant c and up to the additive constant w_0 . As a consequence, the instantaneous velocity trace, calculated in this way, is proportional but not equal to the actual blood velocity.

Pressure waves propagation

The pressure is transmitted along the direction AR-IJV according to the following equation

$$\frac{\partial p}{\partial z} = + \frac{1}{c} \frac{\partial p}{\partial t} \quad (2)$$

For each cardiac cycle, the pressure in the RA reaches its maximum value between t_P and t_Q , where t_P indicates the ECG P wave and t_Q indicates the wave Q. In this note, for the sake of simplicity, it is assumed that the pressure in the RA is maximum in correspondence of the instant t_{PQ} which is the average between t_P and t_Q . The relationship between the pressure in the RA and the pressure in the point G at the same instant of time is given by:

$$p(t + l_G/c, z_G) = p(t, z_{RA}) \quad (3)$$

Where z_G is the coordinate of the US scanning point and z_{RA} is the RA coordinate.

The pressure is, at the same instant t_{PQ} , maximum in the RA ($p(t_{PQ}, z_{RA})$), and equal to $p(t_{PQ} - l/c, z_{RA})$ at the insonation point G. The qualitative JVP trace of

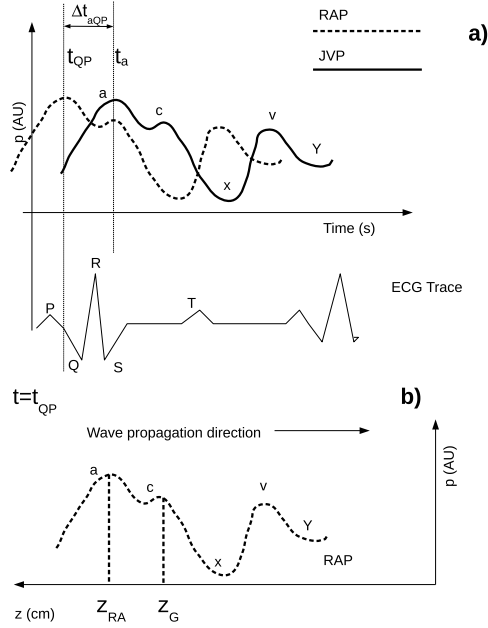


Figure 2: The figure **a)** shows the JVP trace of pressure in the IJV, measured in G, together with the ECG trace. The interval Δt_{aQP} is represented over the curves *a* and QP. In figure **b)** it is shown the pressure along the *z*-axes at instant t_{QP} .

pressure in the IJV, measured in G, can be obtained simultaneously with the acquisition of the ECG trace [Sisini et al.(2016)]. On this trace, that reports both JVP and ECG waves, the time interval Δt_{aQP} between t_{PQ} and t_a is given by:

$$\Delta t_{aQP} = t_a - t_{QP} = \frac{l_G}{c} \quad (4)$$

where t_a is the instant corresponding the *a* wave.

The parameter Δt_{aQP} is the time interval between the instant when the pressure is maximum at point G (instant t_a) and the instant when the pressure is maximum at point RA (instant t_{QP}).

METHODS

The applicability of the relationship expressed in Eq. 4, can be tested by comparing the instantaneous velocity ($\overline{w}(t)$) of the blood in the IJV calculated according to the equation shown above, with the instantaneous blood velocity ($\overline{w}_D(t)$) measured with a Doppler scanner. How-

ever, the data and the results presented here are for illustration only and are not to be considered the result of a scientific study.

Pressure waves velocity calculation

The delay Δt_{aQP} is measured over the JVP+ECG trace as shown in Fig. 2. The distance l_G is measured on the volunteer's chest. The velocity c is the ratio between l_G and Δt_{aQP} .

Compliance calculation

From the Moens-Korteweg equation we obtain the compliance per unit length:

$$C' = \frac{CSA_x}{\rho c^2} \quad (5)$$

where CSA_x is the CSA of the IJV measured in G at the *x* wave.

Pressure gradient calculation

The pressure inside the IJV is calculated from the instantaneous CSA as follows:

$$p(t) = \frac{1}{C'} CSA(t) \quad (6)$$

substituting the expression of $p(t)$ obtained above into Eq. (2) we obtain the expression for the pressure gradient:

$$\frac{\partial p}{\partial z} = \frac{1}{cC'} \frac{\partial CSA}{\partial t} \quad (7)$$

Flow velocity calculation $\overline{w}(t, z)$

The function $\overline{w}(t, z)$ is calculated by inserting into the Eq.(1) the expression for the pressure gradient found in Eq. (7). The mathematical details are given in [Sisini et al.(2015b)].

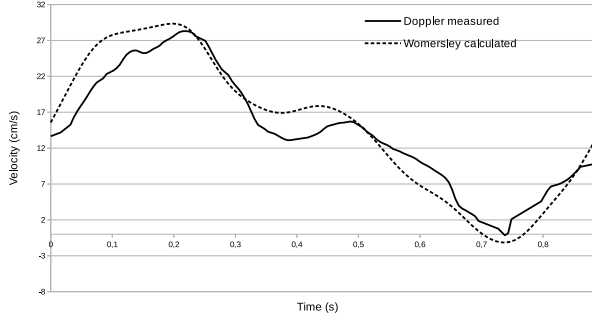


Figure 3: Calculated velocity trace together with the experimental one obtained by the Doppler examination.

RESULTS EXAMPLE

Pressure waves velocity calculation

The measured delay (Δt_{aQP}) was 0.14 s and the distance l_G was 23 cm. As a consequence the velocity c was 164 cm/s.

Compliance calculation

The minimum value of the CSA (CSA_x) during the cardiac cycle was 0.2 cm^2 and the compliance for unit of length was $9.8 \times 10^{-3} \text{ cm}^2/\text{mmHg}$.

Flow velocity calculation $\bar{w}(t, z)$

The velocity was calculated following Eq. (1) and its trace is shown in Fig. 3 together with the experimental trace obtained by the Doppler examination. The two traces in agreement, nevertheless, since the velocity $\bar{w}(t, G+l)$ was calculated up to an additive constant, only the wave amplitude has physical meaning whereas its shift along the velocity axis is not significant.

ACKNOWLEDGEMENT

The author wants to thank Eleuterio Toro for his critical comments to the paper and Giacomo Gadda, Valentina Tavoni and Valentina Sisini to have kindly reviewed the manuscript.

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